Section VI: Whole-Building Computer Simulation—Option D

This section provides information on how to measure and verify savings using Option D—whole-building computer simulation. Chapter 24 introduces Option D and describes the M&V issues associated with using Option D to verify savings for projects with generic variable-load retrofits.

Chapter	Project Description	Method Number
25	Generic variable-load retrofit(s). Generally, projects with multiple ECMs and/or complex measure interactions.	GVL-D-01

24

Introduction to Option D

This section discusses the calibrated computer simulation analysis method of measurement and verification. Use of Option D is appropriate for complex projects in buildings where multiple ECMs will be installed or where tracking complex building operation conditions is necessary. Because a computer simulation allows a user to model the complex interactions that govern building energy use, it can be a very powerful tool to use in estimating a project's energy savings. Even for the simplest projects, however, simulation modeling and calibration are time-intensive activities and should be performed by an accomplished building simulation specialist. Calibrated simulation analysis is an expensive M&V procedure, and should only be used for projects that generate enough savings to justify its use.

24.1 Option D Terminology

This M&V method description uses various definitions of building models and concepts. Below are the key definitions used in describing this procedure:

Existing Building Model: The existing building model is a model of the building as is. All data collected for the existing building will be used to construct the existing building model. These data include the building geometry and materials of construction; building orientation and solar shading; inventories and descriptions of all active building systems, which include the heating and cooling plant, HVAC and lighting systems; plug loads; occupancy rates; and building operation schedules. The existing building model is used as a basis for developing the baseline building model and the post-installation building model. In some cases, the existing building model and the baseline building model are the same.

Baseline Building Model: If performance standards are specified to define the baseline building conditions, adjustments must be made to the existing building model. If this is the case, the baseline building model is a model of the building with equipment (chillers, HVAC, lighting, etc.) efficiencies that comply with minimum efficiency equipment standards. The model is developed from the existing building model. Only the equipment efficiencies (such as lighting kW per lumen, motor efficiency, or chiller kW per ton) of equipment or systems that will be replaced by the ECMs of the project must be changed from those in the existing building model.

Post-Installation Building Model: The post-installation model is a model of the building with all of the proposed equipment efficiency specifications included. It differs from the existing building model and the baseline building model only in the efficiencies of the proposed ECMs. It uses the same descriptions of the building and the same building operation conditions as the existing and baseline building models to determine the post-installation energy usage.

Calibrated Model: A building model is considered to be calibrated if its predictions of whole-building energy usage and its predictions of individual ECM energy usage are in agreement with measured data. Demonstration of this agreement is completed using the statistical comparison techniques described in Chapter 25.

Initial Savings Estimation: The initial savings estimate is required in the initial or pre-installation report and may be determined from the predictions of uncalibrated models. However, the models must be "tuned" using the best available data, such as whole-building usage data from the building's previous 12 to 24 months of utility bills. If other data are available, such as trend logs of specific equipment energy usage from the building's EMCS, then they should also be used to develop the initial savings estimation. The initial savings estimation for each ECM is determined from the difference in annual energy usage between the post-installation model prediction and the baseline model prediction. The procedure used to develop the initial savings estimation should be documented in the M&V plan.

Verified Savings: Verified savings for each ECM are determined from calibrated models after each post-installation year. Annual energy usage for each ECM is determined from the difference in annual energy usage between the calibrated post-installation model prediction and the baseline model prediction. Total verified savings for each ECM must be reported in each regular interval report. The procedure used to determine the verified savings should be documented in the M&V plan.

24.2 Overview of Method

The M&V method described here is based, in part, on materials in draft and final versions of the 1997 IPMVP. Information on the IPMVP can be found at www.ipmvp.org.

The following steps are involved in performing Option D M&V:

- In the site-specific M&V plan, document the strategy for calculating savings.
- Collect the required data from utility bill records, architectural drawings, site surveys, and direct measurements of specific equipment installed in the building.
- Adapt the data and enter them into the simulation program input files.
- Run the simulation program for the existing building.
- Calibrate the simulation program by comparing its output with utility bills and measured data. Refine the existing building model until the program's output is within acceptable tolerances of the measured data.

- If standards must be referenced in the baseline model, adjust the existing model to develop the baseline model. If applicable, adjust the affected equipment efficiencies to represent the standards. If standards are not required, the existing model is the baseline model.
- Repeat the simulation process for the post-installation model. Calibrate the retrofit model with data collected from site surveys (to validate the new equipment and systems are installed and operating properly) and from spot, short-term, or utility metering.
- Estimate the savings. Determine savings by subtracting the post-installation results from the baseline results using either actual weather and facility operating conditions (e.g., occupancy and set points) or typical conditions and weather.
- Document results for the first year of the performance period. Submit all documentation, including electronic files, for approval.
- Annually verify proper installation and operation of the ECM(s) and rerun the computer simulation if either (1) operational characteristics of the measures have changed and/or (2) actual versus typical weather and facility operating conditions are obtained.

These steps are described in detail in Chapter 25.

24.3 Simulation Software

The most frequently used type of building simulation program for energy analyses is the whole-building, fixed-schematic hourly simulation program. Such programs are the most versatile, allowing the accurate modeling of most buildings through input data. Two of the most common public domain programs of this type are DOE-2 and BLAST.

The U.S. Department of Energy maintains a list of public domain and proprietary building energy simulation programs that can be obtained by accessing DOE's information server on the World Wide Web at www.eren.doe.gov. For information on a specific simulation program, please refer to the Web site or the simulation software user manuals.

Simulation programs acceptable for Option D should have the following characteristics:

- Program is commercially available, supported and documented.
- Program has capabilities to adequately model the project site and ECMs.
- Model can be calibrated to an acceptable level of accuracy.
- Calibration can be documented.

Fixed-schematic programs require extensive input data to describe a building. Merely writing all the necessary data into a program's input file can consume a significant part of the project budget. Recently, user interfaces have been developed that simplify the input process with easy-to-use graphical formats. In addition, more extensive libraries of building components, materials, and systems have been added to facilitate model development.

24.4 Model Calibration

The model calibration is accomplished by linking simulation inputs to actual operating conditions and comparing simulation results with whole-building and/or end-use data. The simulation may be of a whole-facility or just for the end use affected by the ECM or system. For whole facility simulations, both levels of calibration should be performed. To obtain end-use data for calibration, building sub-system metering must be included in the project M&V activities (usually during the post-installation period). The specific sub-systems selected for monitoring are in most cases the installed ECMs. For ECMs such as windows or insulation that cannot be monitored, the impacted HVAC system should be sub-metered. The model calibration will benefit the most from the monitoring of the energy end-uses for which the least information is available. An Option D-based M&V plan should include the number of sub-systems to be monitored, and the number of variables, the duration, and the data collection interval for each specific sub-system.

Calibrating a computer simulation of a real building for a specific year necessitates the use of actual weather data. Programs that only allow the use of average weather files or weather data from only a few “representative” periods per month or per season are not suitable for the calibration techniques required for Option D. The measure-specific M&V plan must specify which weather data sources will be used. Both the source of the data and the physical location of the weather station need to be specified. One example of an acceptable weather data source is the National Oceanographic Atmospheric Association (NOAA). The location of the source of data is significant, because some NOAA city data are from weather stations at remote airports, well-removed from a downtown location.

24.5 Determination of Energy Savings

All ECM savings will be determined by the difference in annual ECM usage predicted by the baseline building model and that predicted by the post-installation building model. In the M&V plan and post-installation report submittals, it is desired that ECM savings be reported individually. This means the ECMs must be input consecutively into the baseline building model and simulations run after each is input. Individual ECM savings are determined by the difference in energy use between two consecutive runs. This same procedure should be followed for calculating the initial project savings estimate as well as the verified savings.

24.6 M&V Considerations

Many issues must be considered and addressed in developing the measure-specific

M&V plan. Some of the more common issues are discussed below.

24.6.1 Use an Experienced Building Modeling Professional

Although new simulation software packages make much of the process easier, a program's capabilities and real data requirements cannot be fully understood by inexperienced users. Using inexperienced staff for building modeling will result in inefficient use of time in data processing, model trouble-shooting, and interpreting simulation results.

24.6.2 Availability of Hourly Utility Bill Data

Calibrations to hourly data are generally more accurate than calibrations to monthly data because there are more points to compare. However, hourly whole-building usage data are generally available only for a utility's largest customers. Determine whether hourly or monthly billing data are available and whether meters can be installed to collect hourly data. If only monthly billing data are available, be prepared to use additional short-term monitoring of building sub-systems to improve the accuracy of the model.

24.6.3 Specify Spot-Measurements and Short-Term Monitoring

Spot and short-term measurements augment the whole-building data and more accurately characterize building systems. It is recommended that an end use be monitored over a period that captures the full range of the equipment's operation. The data must also be collected in a way that facilitates comparison to the building model's end-use prediction of the same quantity. Careful selection of spot-measurements and short-term monitoring is necessary because it may add significant cost and time to the project.

24.6.4 Use of the Simulation Program's HVAC System Library

Many software packages have libraries of HVAC systems that may seem to be a good match with the real system. Be cautious and investigate the library HVAC description to be sure it is a good representation of the real system.

24.6.5 Controls

Thoroughness is required to obtain close-to-exact sequencing of building controls. Sequencing of building controls is difficult to interpret from interviews, site surveys, manufacturer's data, and measurements. Be aware that the program's input capability may limit data input for control systems.

24.7 M&V Plan Content Requirements

Specific M&V issues that need to be addressed in the measure-specific M&V plan include:

- Documentation of the project procedure, describing how the initial savings estimate was determined and how the verified savings will be determined.
- Explicit descriptions of data that will be used to calibrate the model. This includes selection of the whole building data (monthly or hourly) and data from specific subsystems that will be collected, including the duration and season of monitoring and the monitoring interval.
- The simulation program and version that will be used, the supplier of the program, and what, if any, pre- and post-processors will be used.
- Existing building description (age, square footage, location, orientation, etc.), including a description of building systems to be replaced by the ECMs of the proposed project.
- Description of any building operation conditions (set-points, schedules, etc.) affected by the ECMs.
- Documentation that the baseline model complies with minimum standards.
- A description of the building data to be collected and their sources (e.g., site surveys, drawings, etc.).
- Identification of spot measurements and short-term monitoring of specific building equipment to be made.
- Identification and source of weather data used (on-site, local weather station, or typical weather data).
- Identification of the statistical calibration tolerances and graphical techniques to be used to demonstrate calibration of the model.
- Indication of who will conduct the simulation analysis, complete the calibration, and document the process.

25

Calibrated Computer Simulation Analysis

25.1 Project Definition

Computer simulations for measurement and verification are used when the energy impacts of ECMs are too complex or costly to evaluate with M&V Option B. Situations for which computer-based building energy simulations are appropriate include any or all of the following:

- ECM savings cannot be readily determined using baseline and post-installation measurements.
- The ECM improves or replaces the building energy management or control system.
- There is more than one ECM and the degree of interaction between them is unknown or too difficult or costly to measure.
- The ECM involves improvements to the building shell or other measures that primarily affect the building load (e.g., thermal insulation, low-e windows).

Conducting a computer simulation is a time-consuming task, and building simulation software programs cannot model every conceivable building and ECM. Situations for which computer simulation is not appropriate include these:

- Buildings that cannot be modeled; for example, buildings with complex geometrical shapes.
- Building systems (HVAC, EMS, etc.) that cannot be modeled; for example, the simulation program lacks the capability to model certain equipment or control algorithms that are important in comparing baseline and post-installation scenarios.
- ECMs that cannot be modeled; for example, some new technologies like ground source heat pumps.
- Projects with limited resources that are not sufficient to support the effort required for data collection, simulation, calibration, and documentation.
- Analysis of ECM savings that can be more cost-effectively analyzed with other methods.

- Anticipated savings that are too small to justify the cost and expense of computer modeling.

25.2 Building Simulation Procedure

25.2.1 Collect Data

The data required for simulating a real building is voluminous. The procedures to collect data for the building and proposed ECMs are described below:

- Obtain building plans. Use as-built building plans if available, or else define alternative sources and submit for approval.
- Collect a minimum of 12 (and preferably 24) consecutive months of utility bills for the months immediately before installation of the ECMs. The billing data should include meter read date, kWh consumption, peak electric demand, and heating fuel use (e.g., natural gas).
- Fifteen-minute or hourly data are also desired for calibration. Determine if building systems are sub-metered. Collect these data if available.
- If hourly data are required to calibrate the simulation, but none are available, consider installing metering equipment to acquire them.
- Determine what data to collect from the building. Develop data-collection forms to facilitate a site survey and keep records of building data. Prepare summary tables to easily check program input.
- Conduct on-site surveys. Visit the building site and collect the requisite data identified in the preceding step. Data that may be collected include:
  - HVAC systems—primary equipment (e.g., chillers and boilers): capacities, number, model and serial numbers, age, condition, operating schedules, etc.
  - HVAC systems—secondary equipment (e.g., air-handling units, terminal boxes): characteristics, fan sizes and types, motor sizes and efficiencies, design-flow rates and static pressures, duct-system types, economizer operation, and control.
  - HVAC system-controls: including location of zones, temperature set-points, control set-points and schedules, and any special control features.
  - Building envelope and thermal mass: dimensions and type of interior and exterior walls, properties of windows, and building orientation and shading from nearby objects.
  - Lighting systems: number and types of lamps, with nameplate data for lamps and ballasts, lighting schedules, etc.

  - Plug loads: summarize major and typical plug loads for assigning values per zone.
  - Building occupants: population counts, occupation schedules in different zones.
  - Other major energy-consuming loads: type (industrial process, air compressors, water heaters, elevators), energy consumption, schedules of operation.
- Interview operators. Building operators can provide much of the above listed information and also any deviation in the intended operation of building equipment. It is critical to note changes in building occupancies that will affect energy use and thus the calibration process.
- Make spot measurements. Record power draw on lighting plug load, HVAC equipment, and other circuits to determine actual equipment operation power.
- Conduct short-term monitoring. Data-logging monitoring equipment is set up to record system data as it varies over time. The data reveal how variable loads change with building operating conditions such as weather, occupancy, daily schedules, etc. The measurements may include lighting systems, HVAC systems, and motors. The measurement period may be from one to several weeks. These data may be required if particular subsystems—such as the chiller plant in a building—need to be modeled accurately in order to determine savings.
- Collect weather data. For calibration purposes, representative site weather data are required. These data may be measured on-site or obtained for a nearby site from the National Climatic Data Center (NCDC). Solar radiation data are not generally available in these data sets, but many programs have modules that simulate solar radiation from the cloud cover values in the NCDC data.
- Model calibration is most effective when the weather files contain real data for the same dates covered by the billing records. After the model is calibrated, the building's energy use may be normalized using average-year weather. Average weather data may be obtained from ASHRAE (WYEC2) and the National Renewable Energy Laboratory (TMY2).
- Document all collected information and inputs in a format that allows due-diligence review. Inadequate or disorganized documentation can be the basis for rejecting a submittal.

25.2.2 Input Data and Run Model

Consult the simulation program's user guide to determine how to properly input the collected data into the model. From the volume of data collected, many decisions must be made to best represent the data in the simulation program's input file. This can be done most cost-effectively by an experienced building-modeling specialist.

After inputting data, run a few simulations to debug the model. Check the model output files to verify that there are no errors in running the program and that the model predictions are reasonable.

25.2.3 Compare Outputs to Measured Data

Using the procedures described in section 25.4, compare the energy usage and demand projected by the model to that of the measured utility data. This step may require some post-processing to view the comparison. All utility billing data should be used in the analysis, electric as well as heating fuels such as natural gas.

The calibration process must be documented to show the results from initial runs and adjustments made to bring the model into calibration. This information, as well as the actual calibration results, needs to be provided in post-installation submittals and annual reports.

25.2.4 Refine Model

If the statistical indices calculated during the previous step indicate that the model is not sufficiently calibrated, revise the model inputs, run the model, and compare its predictions to the measured data again. There are statistical and graphical techniques described in sections 25.4 and 25.5 that reveal where the greatest errors in the model may be found. Pay particular attention to the model's predictions of usage by project ECMs. These results can be plotted and compared with short-term measured data and scheduling information to check for sources of error.

25.3 Model Calibration Procedure

Selecting an approach to calibrate a building model depends on many factors. Among these are the availability of hourly utility bill data and the amount of project savings. After consideration of these and other factors, one of the following three approaches must be selected for calibration:

1. Calibration at the whole building level, comparing model monthly usage predictions to monthly utility bill data;
2. Calibration at the whole building level, comparing model monthly usage predictions to monthly utility bill data in combination with calibration at the subsystem level—i.e., comparing model sub-system usage predictions to measured hourly data; or
3. Calibration at the whole-building level, comparing model hourly usage predictions to hourly utility bill data.

The following three sections describe the required tolerances for model calibration at the whole building level using monthly data, at the sub-system level using hourly data, and at the whole building level using hourly data. Note that for the second approach, if calibration at the whole building level using monthly data is combined with calibration at the sub-system level using hourly data, then the calibration tolerances prescribed in sections 25.3.1 and 25.3.2 both apply.

25.3.1 Whole-Building Level Calibration with Monthly Data

Comparing energy use projected by the building model to monthly utility bills is straightforward. First, the model is developed and run using weather data that corresponds to the monthly utility billing periods. Next, monthly simulated energy consumption and monthly measured data are plotted against each other for every month in the data set, as shown in Figure 25.1. Be sure to calculate the model's whole building energy usage over the same calendar days as for each month's utility bill. The error in the monthly and annual energy consumption is calculated by the following equations:

$$\mathrm{ERR}_{\mathrm{month}}(\%) = \frac{\mathrm{M} - \mathrm{S}_{\mathrm{month}}}{\mathrm{M}_{\mathrm{month}}} \times 100$$

$$\mathrm{ERR}_{\mathrm{month}} = \sum_{\mathrm{year}} \frac{\mathrm{ERR}_{\mathrm{month}}}{\mathrm{N}_{\mathrm{month}}}$$

where *M* indicates the measured kWh or fuel consumption and *S* the simulated kWh or fuel consumption. N_{month} is the number of utility bills in the year.

Note that monthly differences in measured and simulated energy consumption may cancel each other, resulting in a smaller annual ERR. To ensure against cancellation of monthly errors, the coefficient of variation of the root-mean-squared monthly errors must also be checked.

The root-mean-squared monthly error is calculated by the following equation:

$$\mathrm{RMSE} = \sqrt{\frac{\sum_{\mathrm{month}} (\mathrm{M} - \mathrm{S})^2_{\mathrm{month}}}{\mathrm{N}_{\mathrm{month}}}}$$

The mean of the monthly utility bills is:

$$\mathrm{A}_{\mathrm{month}} = \frac{\sum_{\mathrm{year}} \mathrm{M}_{\mathrm{month}}}{\mathrm{N}_{\mathrm{month}}}$$

The CV(RMSE) for the monthly billing data is:

$$CV(RMSE_{month}) = \frac{RMSE_{month}}{A_{month}} \times 100$$

The combination of ERR and the CV(RMSE) can determine how well the model predicts whole-building energy usage. The lower the ERR and CV(RMSE), the better the calibration. Table 25.1 below specifies the acceptable tolerances for monthly and yearly values of ERR for monthly data calibration.

Figure 25.1 Comparison of Measured and Simulated Results (for this example EERyear = 2.5% and CV(RSMEmonth)=10.3%)

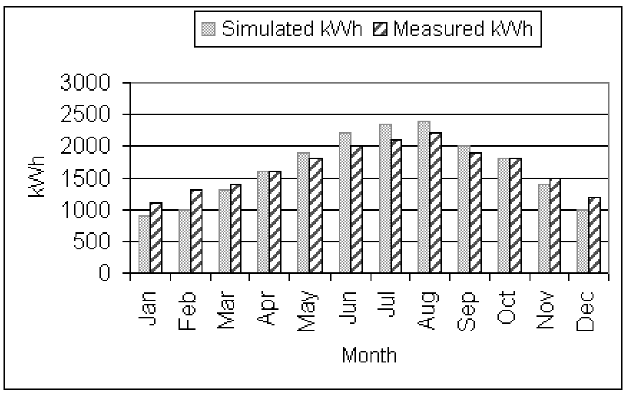

Table 25.1 Acceptable Tolerances for Monthly Data Calibration

Index	Value
ERR_{month}	±15%
ERR_{year}	±10%
$CV(RMSE_{month})$	±10%

25.3.2 Sub-system Level Calibration with Monitored Data

Calibration of a building model's subsystems to measured data may be required to enhance the accuracy of the model. The model's hourly predicted energy usage (kWh, therms, or Btu) is compared to measured hourly energy usage for the monitored building subsystems (the subsystems are to be specified in the M&V plan). Compare the measured and modeled data using the mean bias error (MBE) and the coefficient of variation of the root-mean-squared error [CV(RMSE)] to determine whether the model accurately predicts subsystem level usage. In this case, the MBE is defined as:

$$\mathrm{MBE}(\%) = \frac{\sum_{\mathrm{period}} (\mathrm{M}-\mathrm{S})_{\mathrm{hr}}}{\sum_{\mathrm{period}} \mathrm{M}_{\mathrm{hr}}} \times 100$$

where: M_{hr} is the measured hourly subsystem average usage and S_{hr} is the hourly average predicted usage from the building simulation.

Most simulation programs, including DOE2.1E, output subsystem usage values minimally in one-hour intervals. Therefore for calibration, measured data must be averaged over each hour. For example, 15-minute chiller kW data are collected for exactly four weeks beginning Wednesday, June 23, 1999, at 12 noon. The calibration period consists of the 672 hours spanning the metering start time until 12 noon on July 21, 1999. The RMSE is obtained by squaring the difference between paired hourly data points, summing the squared differences over each monitoring period, and then dividing by the number of points in the monitoring period. The square root of this quantity yields the root-mean-squared error.

The root-mean-square error for the monitoring period is:

$$\mathrm{RMSE}_{\mathrm{period}} = \sqrt{\frac{\sum_{\mathrm{period}} (\mathrm{M}-\mathrm{S})_{\mathrm{hr}}^{2}}{\mathrm{N}_{\mathrm{hr}}}}$$

where N_{hr} are the number of hours in the monitoring period. The mean of the measured data for the period is:

$$\mathrm{A}_{\mathrm{period}} = \frac{\sum_{\mathrm{period}} \mathrm{M}_{\mathrm{hr}}}{\mathrm{N}_{\mathrm{hr}}}$$

The CV(RMSE) is obtained by dividing the RMSE by the mean of the measured data for the monitoring period.The CV(RSME) is:

$$CV(RMSE_{period}) = \frac{RMSE_{period}}{A_{period}} \times 100$$

The values determined for MBE and CV(RMSE) indicate how well the model of the building subsystem fits the monitored data. The lower the MBE and CV(RMSE) values, the better the calibration. Table 25.2 below specifies the acceptable tolerances for MBE and CV(RMSE) for hourly data calibrations.

Table 25.2 Acceptable Tolerances for Hourly Data Calibration for Building Subsystems

Index	Value
MBE_{period}	±7%
$CV(RSME_{period})$	±15%

25.3.3 Whole-Building Level Calibration with Hourly Data

If hourly data are available and calibration to hourly data will be used, two statistical indices are required to declare a model "calibrated." These are the monthly mean bias error (MBE) and the coefficient of variation of the root-mean-squared error (CV(RMSE)).

The mean-bias error is calculated by subtracting the simulated energy consumption from the measured energy consumption for all the hours over a given time period, usually a month or equivalent billing period. The differences are summed and then divided by the sum of the measured energy consumption over the same time period. MBE is expressed as:

$$MBE(\%) = \frac{\sum_{month} (M - S)_{hr}}{\sum_{month} M_{hour}} \times 100$$

where M indicates the measured kWh or fuel consumption and S the simulated kWh or fuel consumption.

The MBE indicates how well the energy consumption is predicted by the model as compared to the measured data. However, it is subject to cancellation errors, where the combination of positive and negative values for $(M\text{-}S)hr$ serve to reduce MBE. To account for cancellation errors, the CV(RMSE) is also needed.[1]

The CV(RSME) is a normalized measure of variability between two sets of data. For calibrated simulation purposes, it is obtained by squaring the difference between paired hourly data points, summing the squared differences over each month or billing period, and then dividing by the number of points, which yields the mean squared error. The square root of this quantity yields the root-mean-squared error. The CV(RMSE), is obtained by dividing the RMSE by the mean of the measured data for the month or billing period.

The root-mean-square error for the month is:

$$\mathrm{RMSE}_{\mathrm{period}} = \sqrt{\frac{\sum_{\mathrm{month}} (M - S)_{\mathrm{hr}}^{2}}{N_{\mathrm{hr}}}}$$

where N_{hr} are the number of hours in the month. The mean of the measured data for the month is:

$$A_{\mathrm{month}} = \frac{\sum_{\mathrm{month}} M_{\mathrm{hr}}}{N_{\mathrm{hr}}}$$

The CV(RSME) is:

$$\mathrm{CV}(\mathrm{RMSE}_{\mathrm{month}}) = \frac{\mathrm{RMSE}_{\mathrm{month}}}{A_{\mathrm{month}}} \times 100$$

The combination of MBE and CV(RMSE) allows one to determine how well a model

1. Kreider, J. and J. Haberl, “Predicting Hourly Building Energy Usage: The Great Energy Predictor Shootout: Overview and Discussion of Results,” ASHRAE Transactions Technical Paper, Vol. 100, pt. 2, June 1994.
Kreider, J. and J. Haberl, “Predicting Hourly Building Energy Usage: The Results of the 1993 Great Energy Predictor Shootout to Identify the Most Accurate Method for Making Hourly Energy Use Predictions,”: *ASHRAE Journal*, pp. 72-81, March 1994.
Haberl, J. and S. Thamilseran, “Predicting Hourly Building Energy Use: The Great Energy Predictor Shootout II, Measuring Retrofit Savings - Overview and Discussion of Results, ASHRAE Transactions, June 1996.
Bou-Saada, T.E. and J.S. Haberl, “An Improved Procedure for Developing Calibrated Hourly Simulation Models,” International Building Performance Simulation Association, Report no. ESL-PA-95/08-01, 1995.

fits the data: the lower the two values, the better the calibration. These indices may be calculated for the entire period, or for weekdays, weekends, and holidays separately (Bou-Saada and Haberl 1995). Table 25.3 below specifies the acceptable tolerances for MBE and CV(RMSE).

Table 25.3 Acceptable Tolerances for Hourly Data Calibration for Whole-Building Data

Index	Value
MBE_{month}	±10%
$CV(RMSE_{month})$	±25%

25.4 Graphical Comparison Techniques

Any or all of four graphical comparison techniques summarized in Bou-Saada and Haberl 1995 may be used to compare a simulation's output with real data. Some of these techniques require significant post-processing of data. These are:

- Hourly load profiles, which compare measured and simulated power for different day-types and seasons. These plots show where the simulation may be under- or overestimating building power.
- Binned interquartile analysis using box-whisker-mean plots, which show both measured and simulated energy use by temperature bins. Such plots allow the statistical characterization of dense collections of points in temperature bins. These plots show how well the simulation is performing in different temperature ranges, as well as the variability in both the measured data and simulation results.
- Weather day-type 24-hour profile plots are also box-whisker-mean plots that show whole-building electricity use versus the hour-of-the-day for both measured and simulated data for different weather day-types. These plots show ambient temperature influences and how well the simulation performs for the different weather periods chosen.
- Three-dimensional surfaces, which are plots of day, hour-of-day, and differences (positive only) between measured and simulated results (negative-only differences are plotted separately). These plots show the modeler when gross differences occur, that may be caused by modeling errors, which can then be checked and corrected, or by building operating conditions that were not accounted for in the data-collection phase of the project. Three-dimensional color plots may be used instead of surface plots. The advantage of color plots is that the plot may be easier to interpret or easier to recognize than time-of-year occurrences of peculiar data.

25.5 Calculation of Energy and Demand Savings

Whether the baseline or the post-installation building simulation is the calibrated model, total energy savings are still determined from the difference between the outputs of the baseline and post-installation model. Savings are determined with both models using the same conditions (weather, occupancy schedules, etc.). It is very important that the baseline and post-retrofit models be consistent in terms of weather and building operation conditions (occupancy schedules, setpoints, etc.).

25.5.1 Select the Appropriate Weather Data Set and Run Both Models

If savings are to be estimated for a specific year, actual weather data from that year must be used. If savings are to be estimated for a typical year, typical weather data files may be used. Both the baseline model and the post-installation model must be run with the same weather data. The weather data to be used are specified in the site-specific M&V plan.

25.5.2 Run Models for Each ECM

So that savings are not double-counted, the ECMs should be input consecutively into the baseline model. After each is modeled, the simulation is run. The first run is the baseline model, the second run is ECM 1, the third run is ECM 1 and ECM 2, the fourth run is ECM 1, ECM 2, and ECM 3, etc. After the final ECM is input, the model should represent the post-installation condition with all ECMs installed.

25.5.3 Calculate Energy Savings.

To calculate ECM energy savings, subtract energy consumption between two consecutive runs. To calculate total savings, subtract energy consumption projected by the post-retrofit model from energy consumption projected by the baseline model. The energy savings determined for the individual ECM should total that determined from the baseline and post-installation runs.

Savings may be quantified using the equation below. The equations are based on total energy savings determined from the difference between the baseline and post-installation runs.

Electric energy kWh savings are calculated with the equation below. Fuel savings (such as natural gas therms, oil volumes, pounds of steam,) for heating or other uses are calculated in the same manner as savings for kWh.

$$kWh_{saved,t} = kWh_{baseline,t} - kWh_{post,t}$$

where:

$kWh_{saved,t}$ = kilowatt-hour savings realized during time period *t*

$kWh_{baseline,t}$ = kilowatt-hour consumption of the baseline building operating under the same conditions (weather, operation, and occupancy schedules, etc.) as the post-installation building, for the selected time period *t*

$kWh_{post,t}$ = kilowatt-hour consumption of the post-installation building operating under the same conditions (weather, operation and occupancy schedules, etc.) as the baseline building, for the selected time period *t*.

When the federal agency pays a flat fee per kWh throughout the year, *t* is one year and the savings calculations are straightforward. When time-of-use charges or other variable usage schedules are applied, the kWh savings must be broken down into the proper categories to determine cost savings.

25.5.4 Calculate Demand Savings

Demand savings are calculated similarly to energy savings. To calculate ECM demand savings, subtract demand between two consecutive runs. To calculate total demand, subtract demand projected by the post-retrofit model from the demand projected by the baseline model. In general, the total project demand savings is determined as follows:

$$kW_{saved} = kW_{baseline} - kW_{post}$$

Demand savings may be based on an average demand reduction or a maximum demand reduction. Average reduction in demand is calculated as the kWh savings during the time period in question (usually the utility summer peak period) divided by the hours in the time period. Maximum reduction in demand is typically the reduction in the utility-metered maximum demand under terms and conditions specified by the servicing utility. For example, the billing peak may be based on the maximum building kW load measured in 15-minute intervals and coincident with the utility peak demand period. The maximum demand reduction is usually calculated to determine savings in utility peak demand charges. Thus, if utility demand savings are to be determined, each site must define (a) how the reduction will affect the utility bill and (b) how the demand reduction will be calculated for purposes of payments to the ESCOs.